

Neutron-Anti-Neutron Oscillation as a Test of Grand Unification¹

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Abstract

We discuss the predictions for the neutron-anti-neutron ($N - \bar{N}$) process in various supersymmetric and non-supersymmetric grand unified theories. In particular it is pointed out that in a class of superstring inspired grand unified theories (of E_6 type) that satisfy the constraints of gauge coupling unification, breakdown of the $B - L$ symmetry occurs at an intermediate scale leading in turn to $\Delta B = 1$ type R-parity violating interactions naturally suppressed to the level of 10^{-5} to 10^{-7} . This in turn implies an $N - \bar{N}$ transition time of order 10^{10} to 10^{11} sec. which may be observable in the next generation of proposed experiments. These models also satisfy the conditions needed for generating the cosmological baryon asymmetry of the right order of magnitude for a restricted range of the parameter space.

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I. Introduction:

The observed matter anti-matter asymmetry in nature is convincing enough as an evidence for the existence of baryon number violation in the fundamental interactions that describe physical processes. This is because of the three conditions for generating this asymmetry laid down originally by Sakharov in 1967: (i) existence of CP-violating and (ii) baryon number violating interactions plus (iii) the presence of out of thermal equilibrium conditions in the early universe. There are also strong theoretical hints in favor of $\Delta B \neq 0$ interactions: for instance, the standard model violates both baryon (B) and lepton (L) number via the triangle anomalies involving the electro-weak gauge bosons (although it conserves the linear combination $B - L$). The present consensus however is that these baryon violating effects are too weak to be observable in laboratory experiments. Similarly, most extensions of the standard model also imply such interactions in the sector beyond the standard model. Perhaps more compelling is the argument that the anomaly free gauge quantum number in most extensions of the standard model is indeed the $B - L$ symmetry alluded to above. If the present indications for non-zero neutrino mass from various terrestrial and extra terrestrial sources hold up with time, the only sensible theoretical way to understand it is to assume that the neutrino is a Majorana particle implying that the lepton number is broken by vacuum by two units ($\Delta L = 2$). Since B and L appear in combination with each other, if lepton number breaks by two units, there is no reason for baryon number not to break. In fact this reasoning was first noted by Marshak and this author[1] as a theoretical motivation for neutron- anti-neutron oscillation.

Once one accepts the existence of baryon number violating interactions, it becomes of crucial importance to learn about the possible selection rules obeyed by them. As is quite well-known[2], the different selection rules probe new physics at different mass scales and therefore contain invaluable information regarding the nature of short distance physics that is otherwise inaccessible. Two of the most interesting selection rules are: one in which $B - L$ is conserved such as the decay $p \rightarrow e^+ \pi^0$ (or $p \rightarrow \bar{\nu}_\mu K^+$ as in supersymmetric theories) and a second one which obeys $\Delta(B - L) = 2$, such as $N - \bar{N}$ oscillation (which is the main theme of this workshop). These two processes probe two very different mass scales. To see this note that the process $p \rightarrow e^+ \pi^0$ arises from the operator $u u d e^-$ (or $Q Q Q L$ in the $SU(2)_L \times U(1)_Y$ invariant form) and it therefore scales like M^{-2} where M denotes the mass scale where the interaction originates. The present limits on proton lifetime then imply that $M \geq 10^{15}$ GeV or so. On the other hand, $N - \bar{N}$ oscillation arises from the operator of the form $u^c d^c d^c u^c d^c d^c$ which scales like M^{-5} . The limits on nonleptonic $\Delta B = 2$ nuclear decays or the $N - \bar{N}$ oscillation time from the ILL

experiment[3], implies that $M \geq 10^5$ GeV or so. Thus $N - \bar{N}$ oscillation has the additional properties that it also provides complementary probes of new physics near the TeV scale.

There is however as yet no laboratory evidence for any kind of $\Delta B \neq 0$ process. The first generation of experiments searching for evidence of baryon number violation have all reported their results as lower limits on the partial life times for the various decay modes of the proton (at the level of roughly 10^{32} to 10^{33} years). Those results have already had the important implication that the minimal non-supersymmetric $SU(5)$ model is ruled out as a grand unification theory. There are currently two experimental efforts to improve the discovery potential for proton decay to the level of 10^{34} years. These are the Super-Kamiokande[4] and ICARUS[5] experiments. To go beyond that would require a major innovation in experimental methods.

There is however encouraging news from the $N - \bar{N}$ oscillation front in this regard. As is well-known[6], the existence of neutron- anti-neutron oscillation inside nuclei leads to baryon instability which can also be probed in the proton decay searches (e.g. the disappearance of oxygen nuclei in water detectors). One can then use simple scaling arguments to relate the nuclear instability life time(τ_{nucl}) to the $N - \bar{N}$ oscillation time ($\tau_{N-\bar{N}}$) For more reliable nuclear physics calculations, see [7]:

$$\tau_{nucl} \simeq \left(\frac{\tau_{N-\bar{N}}}{6.6 \times 10^6 \text{ sec}} \right)^2 \times 10^{30} \text{ yrs.} \quad (1)$$

From this equation we see that a measurement of $\tau_{N-\bar{N}}$ to the level of 10^{10} sec. (as is contemplated by the Oak Ridge group[8]) would correspond to probing baryon instability to the level of almost 10^{37} yrs. This will take us far into the uncharted domain of baryon non-conservation not easily accessible in other experiments(albeit in a very special non-leptonic channel). This may be one of the strongest arguments for undertaking such an experiment. In this article, I will discuss elegant and plausible theoretical models that provide additional arguments in favor of conducting such an experiment since this can be a very useful way to discriminate between various grand unification theories.

This paper is organized as follows: in sec.II, the general theoretical arguments for $N - \bar{N}$ oscillation based on gauged $B - L$ symmetry are outlined; the predictions for $\tau_{N-\bar{N}}$ in non-supersymmetric theories and supersymmetric theories are given in sec.III and IV respectively; in sec.V, it is shown how baryon asymmetry can be generated in an $[SU(3)]^3$ string inspired SUSY GUT model which predicts observable $\tau_{N-\bar{N}}$; in sec.VI, some concluding remarks are presented.

II. Local $B - L$ symmetry and $N - \bar{N}$ oscillation:

As already mentioned, in the standard model, $B - L$ is an anomaly free global symmetry. However, it is not a gaugeable symmetry since it is not cubic anomaly free. This fact is connected with whether neutrino mass is zero or not. In the standard model neutrino mass vanishes because the right handed neutrino is not included in the spectrum; it is also the absence of ν_R that prevents $B - L$ symmetry from being a gaugeable symmetry. In order to generate neutrino mass, we must add ν_R to the spectrum of fermions in the standard model. As soon as this is done, $B - L$ becomes cubic anomaly free and becomes a gaugeable symmetry. This also incidentally restores quark-lepton symmetry to particle physics. The natural gauge symmetry of particle physics then becomes the left-right symmetric gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [9] which then not only explains the smallness of neutrino mass but it also makes weak interactions asymptotically parity conserving. It was noted in 1980[1, 10] that in formula for electric charge in the left-right symmetric model is given by:

$$Q = I_{3L} + I_{3R} + \frac{B - L}{2} \quad (2)$$

It follows from this equation[11] that since $\Delta Q = 0$, at distance scales where $\Delta I_{3L} = 0$, we have the relation

$$\Delta I_{3R} = -\frac{1}{2}(B - L) \quad (3)$$

Clearly, the violation of lepton number which leads to a Majorana mass for the neutrino is connected with the violation of right-handed iso-spin I_{3R} . The same equation also implies that for processes where no leptons are involved, it can lead to purely baryonic processes where baryon number is violated. In nonsupersymmetric theories, the simplest such process is neutron-anti-neutron oscillation since $u^c d^c d^c u^c d^c d^c$ is the lowest dimensional baryon number violating operator that conserves color, electric charge and angular momentum and does not involve any lepton fields. (The situation is different in supersymmetric theories as we will see in the next section.) This equation implies a deep connection between the Majorana mass for the neutrino and the existence of neutron-anti-neutron oscillation. Of course whether $N - \bar{N}$ transition appears with an observable strength depends on the details of the theory such as the mass spectrum, value of mass scales etc.

Before proceeding further, a few words about the notation: Let us call $G_{N-\bar{N}}$ as the strength of the six quark amplitude; $\delta m_{N-\bar{N}}$ as the transition mass for neutron-anti-neutron transition and $\tau_{N-\bar{N}} = h/2\pi\delta m_{N-\bar{N}}$ where h is Planck's constant. We hasten to clarify that while theories with local $B-L$ symmetry provide a natural setting for the neutron-anti-neutron oscillation to arise, it is possible to construct alternative models where one can have $N-\bar{N}$ oscillation. In such models however, the strength for this process is completely unrelated to other physics making them quite adhoc.

III. Predictions for $\tau_{N-\bar{N}}$ in non-supersymmetric unified theories:

There were many models for neutron-anti-neutron oscillation discussed in the early eighties[6]; most of these models are in the context of nonsupersymmetric higher unified theories. Here I present the simplest of them and summarize the general status of $\tau_{N-\bar{N}}$ transition in all these models in Table 1.

We will consider the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$ which was suggested by Pati and Salam[9] in 1973. The recognition that $SU(4)_c$ contains the $B-L$ symmetry and has the potential to explain neutrino mass and applications to $N-\bar{N}$ oscillation came in the papers of Marshak and this author [1, 11]. In order to obtain neutron-anti-neutron oscillation process, the gauge symmetry breaking of the model has to be broken by the Higgs multiplets as in Ref.[11] i.e. a bidoublet $\phi(2, 2, 1)$, and a pair of triplets $\Delta_L(3, 1, \bar{10}) + \Delta_R(1, 3, \bar{10})$. This set of Higgs multiplets was different from the one originally used in Ref.[9] and brought out the physics of the model in a very clear manner. The quarks and leptons are assigned to representations as follows: $Q_L(2, 1, 4) + Q_R(1, 2, 4)$. Here leptons are considered as the fourth color. The allowed Yukawa couplings in the model are given by:

$$L_Y = y_q \bar{Q}_L \phi Q_R + f(Q_L Q_L \Delta_L + Q_R Q_R \Delta_R) + h.c. \quad (4)$$

Here we have omitted all generation indices and also denoted the couplings symbolically omitting charge conjugation matrices, Pauli matrices etc. The Higgs potential of the model can be easily written down; the term in it which is interesting for our purpose is $\lambda \epsilon^{ijkl} \epsilon^{i'j'k'l'} \Delta_{L,ii'} \Delta_{L,jj'} \Delta_{L,kk'} \Delta_{L,ll'} + L \rightarrow R + h.c..$

In order to proceed towards our goal of estimating the strength of $N-\bar{N}$ oscillation in this model, we first note that the original gauge symmetry here is broken by the vev $\langle \Delta_{R,44} \rangle = v_{B-L} \neq 0$ to the standard model gauge group. The diagram of Fig.1 then leads to the six quark effective interaction below the scale v_{B-L} of the form $u_R d_R d_R u_R d_R d_R$ with strength $\lambda f^3 v_{B-L} / M_{\Delta_R}^6$. For the scale v_{B-L}

and M_{Δ_R} of order 100 TeV and for $h \approx \lambda \approx 10^{-1}$ this will lead to a strength for the six quark amplitude of about $10^{-29} \text{ GeV}^{-5}$. In order to convert it to $\delta m_{N-\bar{N}}$, we need the three quark "wave function" of the neutron at the origin. This has been estimated by various people[12] and usually yields a factor of about 10^{-4} or so. Using this, we expect $\tau_{N-\bar{N}} \simeq 6 \times 10^8 \text{ sec}$. This is however only an order of magnitude estimate since the true value of the parameters that go into this estimate is unknown. But the main point that this example makes is that there exist very reasonable theories where neutron-anti-neutron oscillation is observable. Note that this model is a completely realistic extension of the standard model with many interesting features such as the smallness of neutrino mass naturally explained etc.

A natural question to ask at this point is whether there are grand unified theories where observable $N - \bar{N}$ oscillation can be expected. In simple nonsupersymmetric extensions of $SU(5)$ model, it is easy to show that[13] $N - \bar{N}$ transition amplitude is very highly suppressed. Let us therefore consider the $SO(10)$ model which contains the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$. All the ingredients for a sizable $N - \bar{N}$ to exist are present in the model except that the scale v_{B-L} is constrained by gauge coupling unification. This question was studied in detail in Ref.[14] and a scenario of symmetry breaking was isolated where one could get a value for $v_{B-L} \simeq 100 \text{ TeV}$. This would therefore lead to an observable $\tau_{N-\bar{N}}$ oscillation as before. The only problem is that in a low $SU(4)_c$ scale model, one has to introduce iso-singlet fermions to lift the degeneracy between quark and charged fermion masses implied by $SU(4)_c$ symmetry. While this procedure is quite harmless in partial unification models, it effects gauge coupling unification in a model such as $SO(10)$. This question has not been discussed yet in such models. For situation in other non-SUSY GUT theories, see Table 1.

IV. R-parity violation and $N - \bar{N}$ oscillation:

The particle physics of the nineties has perhaps a different "flavor" (set of prejudices ?) than the eighties. It is now widely believed that supersymmetry is an essential ingredient of physics beyond the standard model with supersymmetry breaking scale around a TeV in order to explain the origin of electroweak symmetry breaking. Furthermore if one believes that supersymmetry is the low energy manifestation of the superstring theories, then to the usual renormalizable Lagrangian of the supersymmetric theory, one must add non-renormalizable terms which are the low energy remnants of superstring physics. In the discussion of this section, we will use both these ingredients.

A simple way to explain supersymmetric theories is to note that corresponding

to every particle there is a super partner (spin half partner for a gauge boson or Higgs boson and spin zero partner for a fermion with identical internal quantum numbers in both cases) and there are a large number of relations between the coupling constants of the theory. In this article, we will denote the super partners of quarks and leptons by \tilde{q} and \tilde{L} respectively; super partners of W and Z bosons by \tilde{W} and \tilde{Z} etc. The extension of the standard model to include supersymmetry is under extensive investigation right now both from theoretical and experimental side.

One troubling aspect of the minimal supersymmetric extension of the standard model (MSSM) is that it allows for lepton and baryon number violating interactions with arbitrary strengths. This in a sense is a step backward from the standard model which automatically ensured that both baryon and lepton numbers are conserved to an extremely high degree as is observed. A simple way to see the origin of such terms is to note that \tilde{L} which is the superpartner of the lepton doublet is exactly like a Higgs boson of the standard model except that it carries lepton number. But we know that the Higgs doublet of the standard model couples to quarks; similarly the \tilde{L} field also couples to quarks as in the standard model: $Q\tilde{L}d^c$; but this clearly violates lepton number by an arbitrary amount. Similar terms can be written down which violate baryon number also with arbitrary strength. These are the so-called R-parity violating interactions. There exist very stringent upper limits on the various R-parity violating couplings[15] which range anywhere from 10^{-4} to 10^{-8} depending on the type of selection rules they break. Since the main reason for believing in supersymmetry is that it improves the naturalness of the standard model, it will be awkward to assume that the MSSM carries along with it the above fine-tuned couplings without any fundamental assumptions.

The general attitude to this problem is that when the MSSM is extrapolated to higher scales, new symmetries will emerge which either forbid the R-parity violating couplings or suppress it in a natural manner. A concrete proposal in this direction proposed some time ago[16] is that at higher energies the gauge symmetry becomes bigger and includes $B - L$ as a subgroup. It is well-known that the $B - L$ symmetry is also important in understanding the smallness of the neutrino mass; therefore is not a completely new symmetry custom-designed only to solve the R-parity problem. It is easy to see that in the symmetric phase of a theory containing $B - L$ local symmetry, R-parity is conserved since $R = (-1)^{3(B-L)+2S}$. This however is not the end of the story since the $B - L$ must be a broken symmetry at low energies and if the $B - L$ symmetry is broken by the vev of a scalar field which carries odd $B - L$, then R-parity is again broken at low energies[16]. Examples of theories where R-parity is broken by such fields abound- the string inspired $SO(10)$ and E_6 being only two of them. On the other hand there are also many theories where $B - L$ is broken by fields with even $B - L$ values. In these models[17], R-parity

remains an exact symmetry, as is required if supersymmetry has to provide a cold dark matter particle. It remains to be seen whether these latter class of models can arise from some higher level compactification of superstring theories.

In this paper we focus on the first class of theories since it has been shown that they can arise from string theories in different compactification schemes. In this class of theories, R-parity breaking interactions arise once $B - L$ symmetry is broken. It is then easy to see that to suppress the R-parity breaking interactions to the desired level, $B - L$ breaking must occur at an intermediate scale[18] than at the GUT scale as is quite often done. The reason why all this is of interest to us is that while pure lepton number violating processes in these classes of models are likely to be highly suppressed, the $\Delta B = 2$ processes such as neutron-anti-neutron oscillation may arise at an observable rate. To see what kind of restrictions on R-parity breaking couplings are implied by the present lower limits on $N - \bar{N}$ transition time, let us start by writing down the general structure of R-parity violating interactions in the MSSM:

$$W_{RP} = \lambda_{ijk} L_i L_j e_k^c + \lambda'_{ijk} Q_i L_j d_k^c + \lambda''_{ijk} u_i^c d_j^c d_k^c \quad (5)$$

The coupling relevant in the discussion of neutron-anti-neutron oscillation is the λ'' [19]. Due to the color structure of the coupling, it cannot lead to $N - \bar{N}$ oscillation in the tree level and one has to invoke electroweak loop effects. This has been studied in detail in the recent paper of Goity and Sher[20]. They conclude that the dominant contribution arises from the $u^c d^c b^c$ type coupling in conjunction with a box diagram that changes $dd \rightarrow bb$ and has the strength (see Fig.2):

$$G_{N-\bar{N}} = \frac{6\alpha_{wk}^2 m_{\tilde{W}} m_b^2 V_{ub} \tilde{V}_{ub} \lambda_{123}''^2}{M_{b_L}^8} GeV^{-5} \quad (6)$$

The V_{ub} and \tilde{V}_{ub} above refer to the ub mixing angles in the quark and squark sector. The rest of the notation is self explanatory. The value of \tilde{V}_{ub} is not known. In order to estimate the transition time for neutron-anti-neutron oscillation, we have to multiply by the wave function effect i.e. $|\psi(0)|^2$:

$$\delta m_{N-\bar{N}} = G_{N-\bar{N}} |\psi(0)|^2 GeV \quad (7)$$

Using the value for $|\psi(0)|^2 \simeq 3 \times 10^{-4} GeV^6$ from Ref.[12], we get

$$\delta m_{N-\bar{N}} \simeq 5 \times 10^{-22} \lambda_{123}''^2 \left(\frac{100 GeV}{M_{sq}} \right)^6 GeV \quad (8)$$

The ILL lower bound on $\tau_{N-\bar{N}} \geq .8 \times 10^8$ sec. can be translated into an upper bound on $\lambda''_{123} \leq 4 \times 10^{-6}$. There are uncertainties in this estimate coming from the value of squark mixings as well as the values of squark masses. Our goal will be to seek grand unified theories where values of λ'' in the general ball-park 10^{-6} to 10^{-7} are predicted so that one may confidently argue that those models provide a good motivation for carrying out the neutron oscillation experiment.

We will be guided in our choice of the models by the heterotic superstring theory compactified either fermionically or via the Calabi-Yau manifolds. It turns out that complete breakdown of the gauge symmetry in these cases automatically imply that R-parity, which is an exact symmetry above the GUT scale breaks down. Our goal will be to study the prediction of the strength R-parity violating interactions in these models consistent with the idea of gauge coupling unification. We will discuss two classes of theories: one based on the gauge group $SO(10)$ and another on $[SU(3)]^3$. In both cases we will restrict ourselves to only those Higgs representations allowed by the superstring compactification guidelines.

V. Spontaneous breaking of R-parity in string inspired $SO(10)$ model:

In the $SO(10)$ model, the matter fields belong to the spinor **16**-dimensional representations whereas the Higgs fields will belong to **45**, **54**, **16**+ $\overline{\mathbf{16}}$ 10-dim representations as is suggested by recent studies of level two models[21]. The symmetry breaking in these models is achieved as follows: The vev of the **45** and **54**-dim fields break the $SO(10)$ symmetry down to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which is broken down to the standard model by the $\tilde{\nu}^c$ component of **16**+ $\overline{\mathbf{16}}$ acquiring vevs. The question we now ask is what is the strength of $\Delta B = 1$ R-parity violating terms at low energies. Since the $\tilde{\nu}^c$ field has $B-L = 1$, it will induce the $\Delta B = 1$ terms at low energies. First point to note that they do not arise from renormalizable terms in the Lagrangian but rather only from the mass suppressed nonrenormalizable terms in the $SO(10)$ model. This implies that they are automatically suppressed. The relevant terms are of the form $\mathbf{16}_H \mathbf{16}_m \mathbf{16}_m \mathbf{16}_m / M_{Pl}$. When $\tilde{\nu}^c$ vev is turned on, these type of terms lead to terms of type QLD^c , LLE^c as well as $U^c D^c D^c$. Their strength will be given by $\langle \tilde{\nu}^c \rangle / M_{Pl}$ and will therefore depend on the scale of $B-L$ breaking, which in turn is tied with the gauge coupling unification. Important point to note is that all the above terms have the same strength as a result of which a combination of the QLD^c and the $U^c D^c D^c$ terms at the tree level will lead to proton decay with strength $\simeq \frac{\alpha_W m_{\tilde{g}}}{4\pi M_{sq}^2} \left(\frac{\langle \nu^c \rangle}{M_{Pl}} \right)^2$. The present limits then imply that $\langle \nu^c \rangle / M_{Pl} \leq 10^{-12}$.

This automatically implies that the effective λ'' type terms are also of this order leading to unobservable amplitudes for $N - \bar{N}$ transition.

VI. Observable $N - \bar{N}$ oscillation in $[SU(3)]^3$ model:

Let us now turn to the superstring inspired $[SU(3)]^3$ type models. The matter multiplets in this case belong to representations $\psi \equiv (\mathbf{3}, \mathbf{1}, \mathbf{3})$, $\psi^c \equiv (\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}})$ and $F \equiv (\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1})$ representations. The particle content of these representations can be given by: $\psi = (u, d, g)$, $\psi^c = (u^c, d^c, g^c)$,

$$F = \begin{pmatrix} H_u^0 & H_d^+ & e^+ \\ H_u^- & H_d^0 & \nu^c \\ e^- & \nu & n^0 \end{pmatrix} \quad (9)$$

ψ and ψ^c denote the quark multiplets and F denotes the leptonic multiplets. The Higgs fields will belong to F -type representations and will be denoted by H and \bar{H} respectively. The gauge invariant couplings are then given as in the following superpotential:

$$f\psi\psi^c H + f'(\psi\psi\psi + \psi^c\psi^c\psi^c) + f''\psi\psi^c F + h_1 F^3 + h_2 H^3 + h_3 \bar{H}^3 + \dots \quad (10)$$

where we have suppressed the generation indices. These terms are of course enormalizable. Again as in the case of the $SO(10)$ model, the R-parity violating terms arise once the ν_H^c vev is inserted in the above operators. Again, as before, $\Delta B \neq 0$ terms will be induced by purely renormalizable terms thru tree diagrams of type shown in Fig.3. They lead to $u^c d^c d^c$ type terms[22]. It is these type of terms that are dominant and their strength can be estimated to be $f f' \langle \nu^c \rangle / \langle n^0 \rangle$. The strength of $\Delta B \neq 0$ R-parity violating terms are dictated by gauge coupling unification.

Let us now see the constraints of proton decay on the couplings in this model. To see this, let us recall the superpotential in the above equation. Note that proton decay involves the couplings $f' f''$ whereas $\Delta B = 1$ non-leptonic terms involve $f f'$. Therefore unlike the $SO(10)$ case, the two processes are decoupled from each other and we can suppress proton decay by imposing a symmetry that forbids the f'' term but not the f or f' terms.

Let us now proceed to discuss the constraint of gauge coupling unification on the $B - L$ breaking scale in these models. It turns out that if we assume that $[SU(3)]^3$ breaks down to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ at the GUT scale by the vev of the n^0 field, the spectrum of particles below it is same as for the $SO(10)$

case. We keep one additional color octet multiplet below M_U . The one and two loop unification in this case have been studied recently[23] and the result is that one finds $M_U \simeq 10^{18}$ GeV and $M_{B-L} \simeq 10^{13}$ GeV or so. The one loop unification graph is shown in Fig.4. We see from the discussion in the above sections that operators of type $u^c d^c d^c$ are induced with strength of order λf where $\lambda \simeq 10^{-5}$ as determined by the unification analysis and f is an unknown parameter (which could be assumed to be of order 10^{-1}). This leads to $\lambda'' \simeq 10^{-7}$ or so. It can lead to observable neutron-anti-neutron oscillation with $\tau_{N-\bar{N}}$ of order 10^{10} sec. We hasten to note that due to the unknown coupling f in the six-quark superfield operator, we cannot make an exact prediction; but given the uncertainties in the parameters, the neutron-anti-neutron oscillation time could be somewhere between 10^8 to 10^{10} sec. This is clearly accessible to the proposed Oak Ridge experiment which plans to search for neutron-anti-neutron oscillation upto a sensitivity of 10^{10} to 10^{11} sec.[8]. This should therefore throw light on the nature of this class of grand unified theories.

VII. Baryogenesis in the $[SU(3)]^3$ model:

In the section we present a brief outline of a scenario for baryogenesis in the $[SU(3)]^3$ model discussed above. The reason for this is that the nature of the selection rule for baryon number non-conservation and the possibility of baryogenesis in the early universe are intimately linked. Very crudely this connection can be stated as follows: the higher the dimensionality of the $\Delta B \neq 0$ operator, the lower is the temperature of its thermodynamic decoupling from the rest of the universe. Since before the decoupling temperatures is reached such processes can always erase any preexisting baryon asymmetry, there is a close connection between the mechanism for baryogenesis and the nature of baryon non-conservation. Clearly, since the $N-\bar{N}$ transition operator has dimension nine, it remains in equilibrium to very low temperatures and one must be careful.

We contemplate the following scenario for baryogenesis, where the lepton asymmetry of the universe is generated at temperatures of order 10^9 GeV or so below the temperature for inflation reheating. This lepton symmetry is converted to the baryon asymmetry due to sphaleron effects [24] as suggested in Ref.[25]. We now have to make sure that the $\Delta B = 1$ interaction is out of thermal equilibrium during the time when the sphalerons active in transforming the lepton number into baryon number i.e. from 10^9 GeV down to 100 GeV. In Fig.5, we have plotted the rates for the $\Delta B = 1$ process and the Hubble expansion rates for various values of the λ'' coupling. It appears that only for $\lambda'' \leq 10^{-7}$ or so, the conditions are favorable for baryogenesis. One could also treat this as a crude upper bound on the

magnitude of the $\Delta B = 1$ interaction from the baryogenesis consideration. This corresponds to a $\tau_{N-\bar{N}} \simeq 10^{10}$ sec. It is interesting that this is the range being expected from $[SU(3)]^3$ type theories and is also measurable in the $N - \bar{N}$ experiment being planned.

VIII. Conclusion:

In conclusion, it is clear that a dedicated search for neutron-anti-neutron oscillation to the level of 10^{10} sec sensitivity is going to prove extremely valuable in our understanding of physics beyond the standard model. A non-zero signal would rule out many grand unified theories such as the simple non-supersymmetric $SU(5)$ and E_6 , supersymmetric $SO(10)$ models etc. and will be a strong indication in favor of a string inspired supersymmetric E_6 or $[SU(3)]^3$ type model. A negative signal to this level would imply restrictions on the baryogenesis scenarios and the accompanying particle physics models. A positive signal would also yield valuable information on the violation of equivalence principle between particle and anti-particle.

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Table 1

GUT model	Is $N - \bar{N}$ observable?	Implications
(NON SUSY)		
$SU(5)$	No	$\Delta(B - L) = 0$
$SU(2)_L \times SU(2)_R \times SU(4)_c$	Yes	$M_c \simeq 10^5 \text{ GeV}$
Minimal $SO(10)$	No	
E_6	No	
(SUSY GUT)		
$[SU(3)]^3$	Yes	Induced breaking of R-parity
$SO(10)$	No	

Table Caption: This table summarizes the observability of neutron-anti-neutron oscillation in various GUT models.

Figure Caption:

Fig 1: The Feynman diagram that leads to $N - \bar{N}$ oscillation in the $SU(2)_L \times SU(2)_R \times SU(4)_c$ model.

Fig 2: The diagram responsible for $N - \bar{N}$ oscillation in models with R-parity breaking.

Fig 3: The origin of the $u^c d^c d^c$ vertex in $[SU(3)]^3$ type model at low energies.

Fig 4: The running of gauge couplings in the one loop approximation in models with intermediate scales and unification at the string scale.

Fig 5: The comparison of the rates for baryon number violating processes in R-parity broken models with the Hubble expansion rate.

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